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ABSTRACT

This paper represents one portion of an ongoing effort to elaborate on pedagogical principles based on structural-developmental (largely Piagetian) theory and research. Here, a concept of "problem structure" is developed as a means for identifying physical factors that contribute to children's ability to apply experimental reasoning. Data are presented that demonstrate change in stage of reasoning as a function of change in problem structure: in this case, "mixed" versus "well-separated" variables. It is proposed that level of reasoning results from an interaction between cognitive structure and problem structure. The issue of horizontal decalage (developmental lags) is explicated in these terms. Principles for structuring physical problems for teaching are presented. (RH)

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Cognitive Structure and Structuring Problems for Teaching

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Allen Black

AERA, 1986

Cognitive Structure and Structuring Problems for Teaching

I am concerned with specifying and elaborating pedagogical principles that are based upon the direct application of knowledge of human development to the teaching and learning process in elementary schools. Of principle interest here is the application of structural-developmental principles, particularly principles derived from Piagetian based theory and research. This choice is indicated because the goal of schooling is to promote the acquisition of knowledge in many subject areas, and Piagetian theory and research is both comprehensive and coherent. In developmental terms, it offers a theoretical point of departure that is both differentiated with respect to the development of knowledge in particular areas and integrated with respect to general principles and processes that characterize all knowledge acquisition. I am well aware that the extent to which structural-developmental theory is comprehensive and coherent is disputed. One of the benefits of elaborating upon its application to educational practice is the opportunity to reconsider these controversial issues from a fresh perspective.

At AERA last year (Black, 1985), I gave examples of ways teachers can use expert knowledge of cognitive development in the classroom at three levels of integration of theory and practice. For the most part, the examples were drawn from the practices of student teachers in the Developmental Teacher Education (DTE) program at U.C. Berkeley (Ammon, 1984; Black & Ammon, 1982) and, for the most part, they were concerned with mathematics education.

1. At a first level, understanding the basic genetic epistemological steps in the acquisition of knowledge in specific well-defined subject areas (e.g., number) at a molecular level can facilitate lesson sequencing. In addition, this knowledge, combined with basic principles inherent in the clinical method and in the process of equilibration, quite naturally leads to methods for isolating individual learning problems and for remedial intervention.

2. At a second level, the understanding of what is unique to knowledge acquisition in particular subject areas brings to light ways in which knowledge in one area can interfere with, as well as facilitate or be prerequisite for, knowledge in a related area (e.g., number concepts and spatial-geometric concepts). This understanding can then be used to order, or reorder, the sequence of presentation of curriculum topics within and between subject areas. Integration at this level is local in that it deals with closely related knowledge (e.g., number, space, geometry, time).

3. At a third level, knowledge of the ways in which general characteristics of thought are manifested in diverse subject areas, including areas where fundamental research has yet to be conducted, can provide the basis for an integrated curriculum as well as for

understanding patterns of individual achievement (e.g, arithmetic and writing).

The levels of application summarized represent a progression in the application of expert knowledge of developmental principles that initially involves de-emphasizing general stages in favor of the intricacies of more or less domain specific developments, but later reintroduces considerations of general characteristics of thought at a higher level. Today, I want to establish the groundwork for another application of developmental principles at the second level of integration, this time in the area of science education. This application requires a reconsideration of a general characteristic of cognitive development that has been viewed by many as a central problem for structural-developmental theory.

The general characteristic of thought is horizontal décalage, i.e., ontogenetic lags in conceptual development, such as the typical order of acquisition of conservation concepts during middle childhood: first number, then continuous quantity, length, area, weight. These particular lags, and the existence of developmental asynchonies in general, have been viewed as incongruent with a structural or stage model of development and a good deal has been written about décalage that reflects a concern for this issue (e.g., Flavell, 1982). In brief, if a stage organizes cognitions according to a defined set of structural properties, then once a stage is achieved, these properties should be manifested with respect to all cognitions uniformly. This interpretation is a too static, non-interactive, and closed conception of stage and of the developmental process. It would only apply to a process that was strictly maturational. A better interpretation would

include a conception of stage as a structuring process open to environmental influence that includes diatonic as well as synchronic components. In combination, these components determine the dynamic, individual quality of cognitive development and allow for considerable variation in cognitive activity within a stage.

Similarly, developmental "lag" is not a well-chosen term because it connotes an inexplicable, unexpected irregularity. In fact, and to a large extent, horizontal décalage represents orderly development within a stage, a manifestation of the stage structuring process itself. As it turns out, an understanding of the complexities of the structuring process casts new light on patterns of achievement and also leads to principles of problem difficulty that can be used for matching curriculum to children's levels of concept attainment.

Horizontal Décalage and Problem Structure

I am going to consider horizontal décalage and the stage structuring process from two perspectives. From the point of view of the subject, the sequence represented by a horizontal décalage reflects the dynamics of structural development within a stage. From the point of view of the problem, it reflects a characteristic of problem difficulty which I will refer to as problem structure. The basic hypothesis is that any intelligent judgment is based upon two reciprocal and interactive structures: the cognitive structure of the individual, and the structure of the problem. Today, I will elaborate on this conception with reference to some empirical data and discuss the implications for teaching.

In a study of the development of operational reasoning in adolescents (Black, 1974, 1976), 43 subjects in different age groups

(predominately 6th grade, 10th grade, and college age) were administered ten or more physical problems chosen to encompass different aspects of experimental reasoning (e.g., holding variables constant, producing combinations, understanding compensations, abstracting principles). Because many physical problems were used, an identifiable relationship was revealed between (a) variation among subjects at different levels of cognitive development with respect to making correct causal analyses and (b) variation among physical problems with respect to the ease with which data was extracted and ordered into adequate classifications and co-seriations-- a cognitive level by problem interaction.

In the handout, the nature of that interaction is described in terms of the two perspectives: the structure of the problem, in this case well separated variables versus mixed variables, and the stage level of the subjects. Differences in problem structure are represented by two contrasting physical problems: Inclined Plane and Floating Objects.

The Inclined Plane problem (Black, 1976; Inhelder & Piaget, 1958), depicted on the last page of the handout, was a problem where most of the variables were clearly separated in the raw data. It consisted of a ramp that could be raised or lowered along which marbles of different sizes could be launched. Subjects were asked to discover what factors determined the distance traveled by the marble. The distance traveled was a function of two first order, easily identifiable variables: the slope of the ramp and the distance along the ramp from which the marble was launched. The size/weight of the marble was not causal. A second order variable, that was causal but was not easily identifiable, was just the absolute vertical height from which the marble was launched.

This was a second order variable in that it was not clearly delineated in the raw data and needed to be abstracted through an analysis of the interaction of the first order variables.

In contrast, Floating Objects (Black, 1976; Inhelder & Piaget, 1958) was a problem with causal variables that were not clearly separated in the raw data at any level. Subjects were presented with a large group of objects of disparate sizes, shapes, weight, and materials, together with a bucket of water and asked to determine why things float. Although there were some unit-sized objects made of various materials in the set of objects, and means to obtain equal volumes of water for comparing weight per volume using a pan balance, neither the first order variables (size, weight, material, amount of water, variety of liquid, etc.), nor the second order variables (volume, density, specific gravity), were easily identified.

In Table 1, the level of solution to the problems is charted in the body of the table as a function of stage level and problem structure. The sequence of achievement for the Inclined Plane problem with well separated variables was fairly close to what might be presented as typical or characteristic of the various substages. For example, co-seriations between the easily identified variables were explored early in the development of concrete operations when seriation and co-seriation schemes develop. In contrast, the sequence of achievement for the Floating Objects problem "lagged" about one substage. For example, there were instances of precausal (i.e. preoperational) reasoning at the level of concrete operations, and causal variables were neither identified nor manipulated in any systematic fashion until the level of formal reasoning. To highlight the influence of problem

structure on level of reasoning, the décalage is also summarized in Table 2 in terms of the substages where increasingly complete solutions were achieved.

As can be seen in Table 1, children who performed at the beginning level of concrete operations on most problems immediately established fairly exact co-seriations between length of trajectory of the marble and the slope of the ramp on the Inclined Plane. However, they tended to overlook distance along the arm as an important variable and the compensatory relationship between slope and distance along the arm was not considered as important even when it was pointed out. Where variables were mixed, as with size/weight of the marble, causal judgments tended to be confused and to exhibit characteristics of preoperational reasoning (e.g., single levels of a variable were inaccurately identified as causal--"the smallest one goes furthest").

When working with the Floating Objects problem these same subjects were unable to establish any systematic co-seriations between independent variables and the dependent variable floating versus sinking. The material the object was made of began to be differentiated as a causal factor, but since subjects were unable to systematically control the dependent variable, forms of reasoning generally associated with the preoperational stage were still found (e.g., boats float "because they have sails that billow in the wind that make them float and some have motors that keep them on the water"). Thus, there was lack of correspondence in reasoning for the two problems when there was a difference in problem structure but a similarity when there was a similarity in problem structure.

Subjects at a later substage of concrete operational reasoning

became more facile coordinating first-order variables on the Inclined Plane problem. The roles of slope and distance along the ramp were clearly recognized and the compensatory relationships between them were used to control outcomes with facility. However, the size/weight of the marble was only reluctantly excluded as causal and vertical height was not discovered as an effective variable and continued to be rejected when it was suggested.

With the Floating Objects problem, the same subjects were unable to isolate causal variables and relationships between variables were not accurately assessed. Although there were advances in conceptualizing causal factors (e.g., a qualitative conception of density), there were also inaccurate formulations of causal variables (e.g. shape) and instances of preoperational forms of reasoning (e.g., active forces) persisted. In many respects the experimental reasoning displayed by late concrete reasoners on this problem paralleled the reasoning of early concrete reasoners on the Inclined Plane problem.

Early in the stage of formal reasoning the only advance in performance on the Inclined Plane problem was a more systematic form of experimentation with the first order variables. The second order variable vertical height, although appreciated more, was still rejected as a single causal variable. At this same substage, the effective variables in the Floating Objects problem were beginning to be isolated and their roles accurately demonstrated (e.g., volume and density). However, the concept of specific gravity was not constructed and extraneous variables continued to be introduced (e.g., boats float because they have air in them). For one problem there was systematic experimentation, for the other only guided exploration at this substage.

It was not until later in the stage of formal reasoning that the lag in conceptual development between the two problems narrowed. At this point, the role of vertical height was isolated for the Inclined Plane problem, and the concept of specific gravity was accurately applied to the Floating Objects problem.

The implications of the data are clear. A judgment about a form of reasoning can not be made without considering the nature of the problem. It is not that different problems elicit different stages of reasoning, but rather, that the structure of the problem contributes to the level of solution by setting limits on the possibilities for the individual to structure stage consistent schemes (e.g., ordering increments of stick length vs. increments of abstract physical forces). Further, development within a stage is largely a matter of increasing the zone of application of basic structuring schemes and, most importantly, their coordination. A model for conceptualizing the organization of both lower level and higher level schemes within a stage of development has been proposed by Langer (1969) and is consistent with the data.

Once a stage is recognized as a structuring process and not a static entity, developmental asynchonies can be used to better understand the truly interactive quality of the developmental process. Reciprocally, knowledge of problem structure can be applied to educational practice as a means for structuring problems in the classroom to match various levels of existing knowledge. However, before I proceed with the latter topic, I want to note that the concept of problem structure does not exhaust the topic of developmental asynchronies (cf. Case, 1982) but it takes a significant step in that direction.

Problem Structure and Learning

To elaborate on the topic of structuring problems for teaching, it is helpful to consider data on efforts to teach the basic concepts involved in the physical problems discussed. For this part of the research 27 subjects were selected on the basis of their performance on six pretest problems and placed into one of three groups. One group designated Concrete was composed of subjects who were assessed consistently within the concrete stage and predominately at the consolidated level. A Transitional group was defined largely by stage mixture; on some problems subjects were assessed at the concrete stage and on others at the early formal substage. An Early Formal group was composed of subjects who were assessed at the formal level on almost all the problems but the reasoning was not consolidated. Seven subjects in each group were taught and two served as controls.

Subjects were taught individually on the six pretest problems plus several others that covered important concepts necessary for solutions to the problems. The subjects were then posttested on four of the six pretest problems plus four new problems to assess generalization. The typical sequence took 10 weeks: two, two-hour pretest assessment sessions; four, once a week, two-hour training sessions; a one-week break; then two, two-hour posttest assessment sessions.

The Floating Objects problem was used for pretesting, training, and posttesting. The results are given graphically in Figure 1. Each group's performance is represented by a triangle within the graph. The level of solution is given by substage on the y-axis and the x-axis indicates when the assessments were made. "Pre" indicates pretest; "DT" abbreviates direct tuition, that is, what the subject was able to

accomplish with the teacher actively teaching; and "Post" indicates posttest. Unfortunately, the Inclined Plane problem was only given at posttest, so I have chosen another problem with well-separated variables to compare with the results for Floating Objects. The Chemical Yellow problem is also depicted in the handout. The problem for the subject was to discover what combination of liquids produced the color yellow, or in general, to identify the role of each chemical. Although this is a problem involving combinations rather than co-seriations there is a similarity with respect to identifying, isolating, and manipulating variables. The same point could be made by considering different components of several problems but that is too cumbersome here.

For both of the problems considered here, there was a statistically significant pretest to posttest advance for the experimental group taken as a whole compared with the control group (about one-third stage). With respect to the debate over the existence of stages, these results merely reflect additional evidence for the existence of limits on inducing stage advance that have been demonstrated for various domains of knowledge (e.g., Inhelder, Sinclair, & Bovet, 1974; Blatt and Kohlberg, 1975; Turiel, 1966). Of more importance for education is the nature of the conceptual advance demonstrated by students at the various levels of operational reasoning who were given very similar instruction. Although the numbers of subjects in the operational group were too small for statistical comparisons of group learning, it should be clear from the graphs that they were grouped by problem interactions.

Of particular interest is the performance with the Floating Objects problem of the group designated Concrete, all of whose members were sixth graders. For this group very little knowledge of density or

specific gravity was assimilated even when the teacher was modeling the concepts and encouraging their active construction. These sixth graders were never really able to isolate and manipulate the first level variables, and hence, were unable to appreciate or comprehend the beauty of the solution to the problem of why objects float.

This type of response to teaching was also noted for subjects in the Concrete and Transitional groups at the end of the posttest assessment on the Inclined Plane problem. At that time, the role of absolute height was first suggested, then demonstrated. The Concrete group refused to accept the idea, and the Transitional group assimilated the role of absolute height to one of the other variables but not reciprocally. If only these results are considered, the outlook for teaching experimental reasoning or even much about basic physical concepts to sixth graders is not good. However, the outlook for teaching changes when the results for the Chemical Yellow problem are considered.

During direct tuition subjects in the group designated Concrete were able to produce fairly systematic combinations of chemicals, and to increase their performance at posttest. Although their level of analysis remained at the level of an empirical investigation, rather than a true experiment, the basic nature of the problem was appreciated, and some basic procedures for the systematic production of combinations could be assimilated to their repertoire of problem solving schemes. Similarly, during direct tuition with the Floating Objects problem, subjects in the group designated Transitional were able to appreciate the problem, and to engage in active learning. Their performance at posttest improved considerably.

From a positive, educational perspective, the results indicate that students at different levels of cognitive development can learn different things from the same problem, and reciprocally, that there is something to be learned from almost any problem for almost any student. In considering what is to be targeted for learning, the results taken as a whole (Black, 1976) have some clear implications for how to structure physical problems for teaching and for expectations about levels of experimental reasoning in elementary school classrooms.

1. Children in the primary grades, who are typically in the early phases of concrete reasoning, are oriented more toward demonstrations of effective causal linkages than toward experimentation. They are mostly limited to considering the action of single, well-separated variables successively, unless the simultaneous action of additional well-separated variables are continually emphasized. They also have difficulties comprehending compensatory relationships except where there is an almost automatic connection between variables and a good deal of familiarity with their action (e.g., weight and distance on a balance beam). As was noted with the size/weight of the marble in the Inclined Plane problem, children at the early concrete operational stage are reluctant to give up (exclude) variables that are compelling, even when there is no evidence for their effect in the raw data.

2. Children in the upper elementary grades have some feel for experimentation (i.e., semi-systematic investigations) and can explore and comprehend causal relationships between easily identified independent and dependent variables. They can also produce a limited set of systematic combinations of variables so that simple interactions between clearly presented variables, such as slope and distance on an

inclined plane, or weight and distance from the fulcrum on a balance beam, can be appreciated easily. On the other hand, children late in the stage of concrete operations have difficulty grasping the meaning of second order variables like absolute height, density, and specific gravity, that require abstraction from the interactive effects of first order variables. However, they can gain some intuitive understanding of concepts such as density, if they can be explored concretely, for example, by adding weight to a fixed volume while observing the continuous displacement of water.

3. During adolescence, children begin to be able to handle compensations and combinations that are more complex, and to understand the action of higher order variables that require abstraction from information gathered from the interaction of lower level variables. As the development of formal reasoning progresses, individuals become more facile with these kinds of relationships. However, it seems to require some appreciation and understanding of physics as a science, that is, as a particular means for evaluating knowledge, for students to actively pursue the construction of closed systems. These psychological findings support the epistemological claim that physical causality is a domain of knowledge in its own right that cannot be reduced to logic.

4. Familiarity with variables is an important factor that intervenes between the individual and any type of problem encountered. Its importance reflects the basic theoretical proposition that thought has its origins in action, which is also directly responsible for the psychological-epistemological linkage just described. The teaching results indicated that even when the the necessary logical competence of the subjects and the difficulty level of the concept were well matched,

new variables or concepts needed repeated exposure in a number of related physical experiences to be abstracted or even to be accepted during direct instruction. These results offer additional support (Shymansky, Kyle, & Alport, 1982) for providing concrete, hands-on experience to elementary school-age children as the method of choice for teaching science concepts. The results do not support the increasingly common practice of reducing science education to a collection of facts that can be acquired as another reading activity.

Structural Development and Structuring for Learning

I have attempted to demonstrate one important way that structural developmental theory and research can be used as a central component in elementary school pedagogy. One reason elementary school is targeted is because important stage developments occur during this period and these developments have important implications for what subject matter is presented and how subject matter is presented if it is to be understood, that is, genetic epistemological considerations.

Structuring curriculum is not merely a matter of matching subject matter to students in a single application but also involves lesson planning over time that takes into account the recursive processes involved in knowledge acquisition. These structuring processes are reflected in the need for establishing "spiral curriculum" and "learning cycles" in the various senses discussed by Resnick and Ford (1981). In the cognitive developmental literature they are reflected in a number of ways, for example, in the appreciation, comprehension, reproduction phases of knowledge acquisition (Rest, Turiel, & Kohlberg, 1969; Rest, 1973) as well as in the limits set on knowledge acquisition within the various domains of knowledge.

Structuring problems for learning requires knowledge of the stage structuring process. Reciprocally, knowledge of the stage structuring process makes sense out of a lot of data on knowledge acquisition that is seen by some as incongruent with structural developmental theory. As I have tried to demonstrate, décalage is a necessary corollary for a developmental theory that is constructivist rather than purely maturational. For the most part, it represents the environmental component in the basic Subject X Object interaction equation that characterizes the basic developmental process.

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Table 1

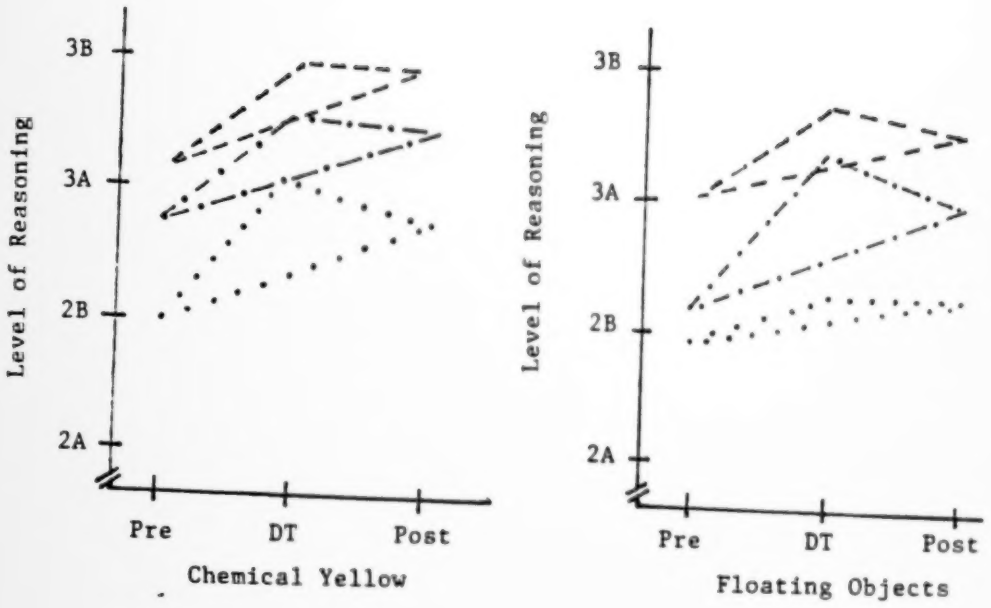
Experimental Reasoning as a Function of Level of Cognitive Development and Problem Structure

	Problem Structure	
Level of Cognitive Development	Well Separated Variables (e.g., Inclined Plane)	Mixed Variables (e.g., Floating Objects)
Early Concrete Operations	Exact correspondences between at least one independent variable and the dependent variable except where variables were mixed (e.g., height of plane, distance on plane, but not size/weight of marble)	Pre-causal reasoning (size and weight confused)
Consolidated Concrete Operations	Facile compensations between independent variables. Size/weight of marble only reluctantly excluded	Some residue of pre-causal reasoning that parallels limited separation of causal variables (e.g., size and weight)
Early Formal Operations	More facile coordination of first-order variables, but the role of absolute height is not abstracted. Size/weight of marble firmly excluded	Identification of first order causal variables (weight and volume, some density)
Consolidated Formal Operations	Identification of second order causal variable (absolute height)	Identification of second order causal variables (density and specific gravity)

Table 2

Stages of Cognitive Development Where Levels of Experimental Reasoning are Manifested for Problems of Different Structure

	Problem Structure	
Levels of Experimental Reasoning	Well Separated Variables (e.g., Inclined Plane)	Mixed Variables (e.g., Floating Objects)
Identification and control of first order variables	Early Concrete Operations for one variable and successively for two variables (height of plane, distance on plane)	Intuitively at Consolidated Concrete Operations -- more precisely at Early Formal Operations (e.g., weight and volume)
Identification and control of compensatory relations between first order variables	Consolidated Concrete Operations	Early Formal Operations (volume and weight)
Abstraction of second order variables	Consolidated Formal Operations (absolute height)	Consolidated Formal Operations (specific gravity)

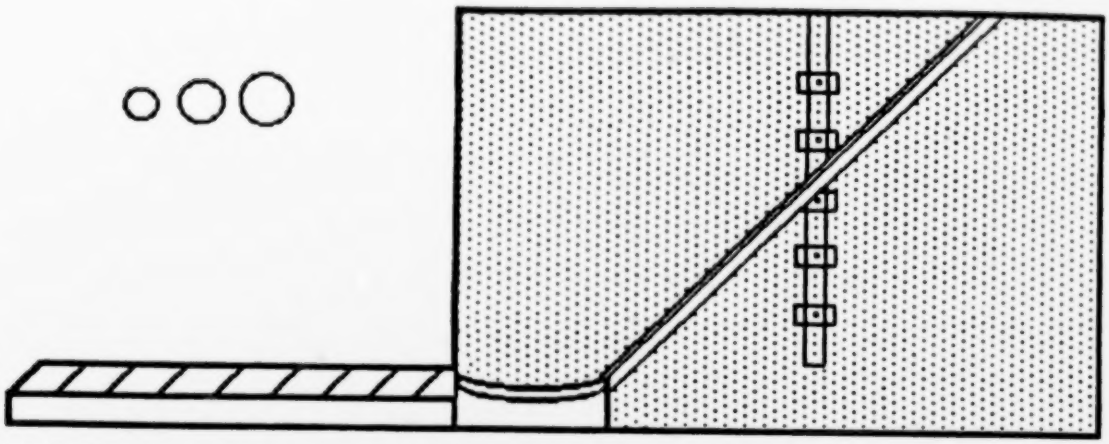


Concrete . . . . . Transitional —.—.—.—.—.

Early Formal — — — — — —

Figure 1. Learning Curves for the Chemical Yellow and Floating Objects Problems.

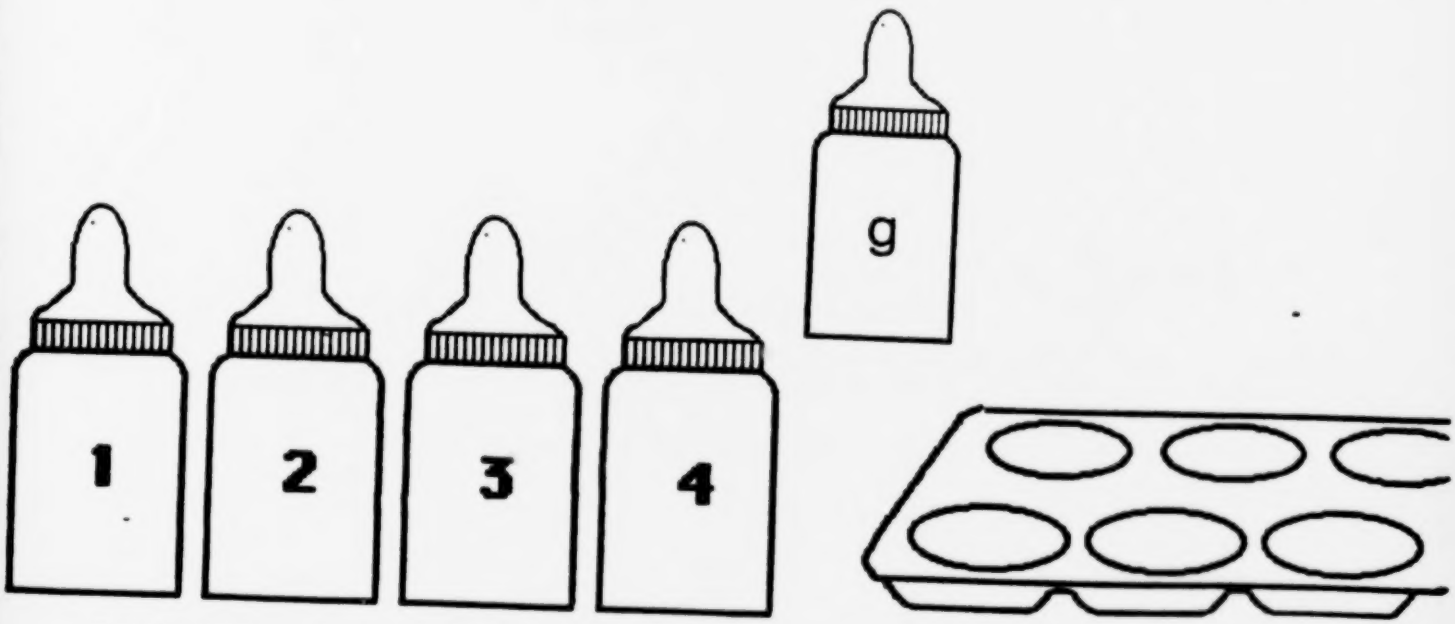
Inclined Plane: Posttest



Effective variables: slope, distance along the arm, vertical height

Ineffective variable: size-weight of marble

Chemical Yellow: Pretest, Training, Posttest



Bottle contents	Action
1. sulphuric acid	produces yellow only when mixed with 3 and g
2. water	no effect, neutral with 1 and 3 and/or 4
3. hydrogen peroxide	produces yellow when mixed with 1 and g
4. sodium theosulphate	bleaches color and prevents it
g. potassium iodide	produces color with 1 and 3 (activator used with all combinations)

Active combinations: 1 x 3, 1 x 2 x 3